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The NATO Defence Research Group Workshop on Function Allocation

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ABSTRACT

From a review of human engineering analysis techniques in use in different nations, conducted from 1988 to 1991, a NATO Research Study Group concluded that Function Allocation was the weakest of the available classes of techniques. As a result the Group organised a workshop on "Improving Function Allocation for Integrated Systems Design." The workshop concluded that the need for function allocation is clear: it is an integral part of the process which synthesises a design solution for a particular system. The maturity of the recommended function allocation techniques is questionable: the approach to function allocation has not changed significantly in three decades. No new techniques for function allocation were discussed at the workshop, although applications of improvements to existing approaches and a wide range of factors which should be included in the function allocation decision were reported. It became clear that it is important to test function allocation decisions as early as possible in the system development process through computer simulation, rapid prototyping, part-task simulation or human-in-the-loop simulation. Directions for future research which were identified included the systematic compilation of information about function allocation issues and improving the techniques used for testing the function allocation decision.

1. Introduction

One of the earliest references in the human factors literature defines the aim of Function Allocation as "the determination of the activities to be performed by humans" (Van Cott & Altman, 1956). More formal definitions place emphasis on the "assigned division of required functions to one or more human, machine and /or computer elements" (North, Stapelton & Vogt, 1982). Such definitions have been described as simplistic (Meister, 1987). More broadly, function allocation is about trade-offs between technology and human performance of tasks in a system and the assignment of function to one or more generic system elements (Pressman, 1987).

In a review of human engineering analysis techniques in use in different nations, conducted from 1988 to 1991, a NATO Research Study Group (RSG.14) concluded that function allocation was the weakest of the available classes of techniques (Beevis, et al., 1992). Those reportedly used in design projects were limited in scope and detail and those recommended in the human factors literature had not matured in two decades. Most techniques used an ordinal level of measurement i.e., 'man is better at ....' 'machines are better at ....'. As a result few such analyses could be related directly to system performance

requirements. Consequently, there were few opportunities for quality assurance of function allocation analyses.

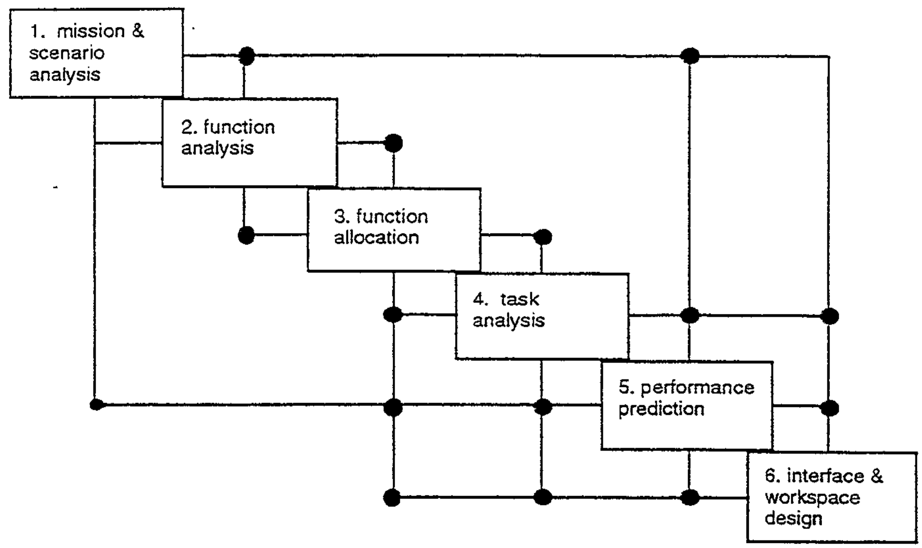

Figure one. N2 diagram of information flow in the series of human factors engineering analyses studied by NATO RSG.14 (vertical lines are inputs; horizontal lines are outputs)

The NATO Research Study Group concluded that there were several good reasons for trying to improve the approach to function allocation. Those reasons relate to: (a) the contribution that function allocation can make to the systems engineering process; (b) developments in the systems engineering process itself, and; (c) the contribution of human operator costs to system costs.

Function allocation is a central activity in a sequence beginning with the specification of the functions that should be performed, and is followed by the evaluation of the consequences of one of more design options (Figure one). It is an integral part of the Systems Engineering process (Pressman, 1987), although it may be hidden as an initial stage in design synthesis or performance allocation (Fabrycky, 1989). While some current systems engineering texts mention function allocation for hardware and software they do not cover the topic of human-machine function allocation well. When they do perform function allocation, systems designers often assign functions or tasks to humans based on engineering criteria rather than human factors, for example, what functions can be automated within given cost limits (e.g., Chapanis, 1970). This reflects the fact that designers are more comfortable using quantitative criteria than material that is qualitative or verbal (Meister, 1987). Yet function allocation is the first major contribution that a human factors specialist can make to the system design process (Chapanis, 1960) and provides a significant opportunity to influence the human factors aspects of the system.

Developments in the system engineering process require complementary improvements to human factors engineering techniques. At the same time same new approaches to system development may provide opportunities which can be exploited by human factors specialists. For example, function allocation techniques that have been developed within the computer

science or software development community may provide an opportunity for establishing a common approach to such problems.

Cost reductions have become a major thrust in the development of new systems. Systems Ergonomics (or the more recent term, Human System Integration - HSI) attempts to control life-cycle costs by making trade-offs between selection, training, and equipment design. Making such trade-offs increases the number of degrees of freedom in the function allocation process compared with a simple decision based on the costs of performing a function using a computer rather than a human. Although the seminal paper by Fitts and his colleagues (1951) on function allocation included training and maintenance of skills as economic factors, many published approaches to function allocation do not deal well with personnel and training factors.

2. The NATO Function Allocation Workshop

Following up on these conclusions, the NATO Group organised a workshop on "Improving Function Allocation for Integrated Systems Design." The aim of the workshop was to review: the need for function allocation; the maturity of available techniques, and; the need for additional research in the area, and to make recommendations to human factors practitioners. Seventeen presentations drew on practical experiences in function allocation to review the need for improvements and for additional research. Applications which were reviewed included aircraft (Beevis; Goom; McDaniel; Knapp; Onken; 1996), ships and ship systems (Boer; Bost & Oberman; Malone; Nordø & Bråthen; Swartz & Wallace, 1996), land vehicles (Papin & Ruisseau; Streets & Edwards, 1996), and command and control systems (Berheide, Distelmaier & Döring; Campbell & Essens, 1996).

3. The importance of function allocation

The presentations and workshop discussions made clear the need for, and importance of, function allocation. Workshop participants' experiences confirmed that function allocation is an integral part of the systems design process. That design process includes a top-down decomposition of system requirements to the point where a solution can be synthesised (McDaniel; Nordø & Bråthen, 1996). Function allocation contributes to that design synthesis (Aymar; Onken; Goom, 1996). In Figure 2 the allocation process is represented as essentially a synthesis activity where criteria from different dimensions are merged or a incorporated in a trade-off analysis.

It was also clear that the need for cost reduction is encouraging systems designers to implement ever more automation. Given that manpower costs in many systems can account for 50% of life cycle costs (Bost & Oberman; Malone, 1996) systems developers support the need to reduce manning levels or, in some cases they may have reduced manning levels imposed on the system (Streets & Edwards, 1996). Because total automation cannot be achieved, human factors specialists must focus on function allocation:

- in order to maintain control over the human-machine relationship and ensure that the role of the human is defined and understood (Berheide et al.; Boer, 1996);
- to ensure the cost benefits of automation (Bost & Oberman, 1996) and thereby, operator reliability (Boer, 1996), and;
- to control operator workload (Goom; Malone; Swartz, 1996) in one case by increasing manning levels (Knapp, 1996).

Another reason that automation is being implemented for tasks now performed manually is to increase the speed and/or volume of information transmitted or to increase the reliability of information handling (Berheide et al.; Campbell & Essens; Onken, 1996).

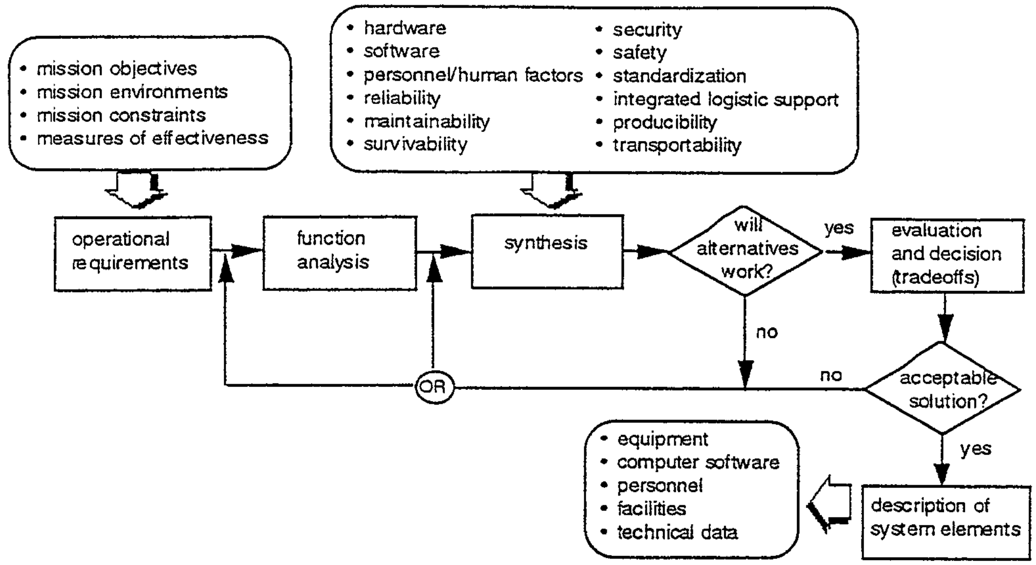

Figure two. The systems engineering process. (from Beevis, et al., 1992, after US Defense Systems Management College)

In summary, function allocation is related to issues of automation and personnel reduction as well as to questions about human responsibility for the safe and effective operation of a system. The steadily improving capabilities of hardware and software complicate decisions about how to balance human factors considerations against political, financial, managerial and performance constraints. A formal review of those issues is essential, and function allocation provides that review.

4. Limitations of existing techniques

The experiences reported by delegates to the NATO workshop reinforced the conclusions of the workshop organisers about the limitations of function allocation techniques. The techniques do not seem to have evolved or matured. Many function allocation decisions are being made on the basis of largely intuitive information (Streets & Edwards, 1996) or what might be called 'Statements of the Blindingly Obvious' (SOTBOs) (Goom, 1996).

Unfortunately, there are no infallible rules to define human proficiencies at the general level of description which is often used in such statements (Onken, 1996). Such information cannot support the kinds of trade-off decisions made in the engineering design process (Bost & Oberman, 1996). This lack of data means that the effectiveness of function allocation decisions cannot be evaluated at the conceptual level where they are made (McDaniel, 1996). Nor do the function allocation techniques described in the literature address all of the issues involved in allocating functions. Several presentations emphasised the importance of including organisational factors in the allocation decision (Aymar; Beevis; Streets & Edwards, 1996).

Table one. Range of criteria from selected papers

Fitts (1951)	Kantowitz & Sorkin (1987)	Drury (1994)
a. Comparative performance Sensory functions Perceptual abilities Flexibility Judgement Selective recall Reasoning Speed and power Routine-work Computation Short-term storage b. Economic issues c. Technical Feasibility d. Manpower and personnel problems Training Maintenance of skills Job life Equipment maintenance and calibration Overloading Flexibility	a. Cost b. Performance c. Reliability d. Maintainability e. Personnel requirements f. Safety	a. System effectiveness Errors/reliability Speed Maintainability Limiting weight/size b. System efficiency Initial cost Running cost Disposal cost c. Human well-being Safety Health Satisfaction

Given these limitations, it is not surprising that the concept of formally allocating functions to humans does not fit in with the engineers' concept of function allocation, particularly function allocation in software systems (Nordø & Bråthen, 1996). At the same time it was argued that 'traditional' allocation of function is not appropriate to the development of software systems because the roles of humans and computers are conceptually different (Campbell & Essens, 1996; Meister, 1991). This reflects the arguments of Fitts (1963) that a list of ways in which man is superior to machine is misleading and Jordan (1963) that humans and machines are not comparable.

5. Practical function allocation criteria

A number of authors have reviewed a wide range of criteria which are applicable to function allocation (Older, Waterson & Clegg, 1997; Price, 1985; Van Cott & Altman, 1953). The seminal review by Fitts and his colleagues (1951) covered a broad range of criteria. Kantowitz and Sorkin (1987) emphasised systems relevant criteria, and Drury (1994) restructured the list and included human well-being (Table 1). The range of criteria which workshop participants reported they had used for making the function allocation decision ranged from systems or operator performance and operator workload, cost, technical feasibility and political and managerial constraints, and health and safety (Figure three).

These criteria are recommended already in the human factors literature. Although previous reviews addressed operator skills (Fitts, 1951) and grading of human tasks to match individual differences and job satisfaction (Singleton, 1974) not much has been published that assists systems developers to consider such factors in practice.

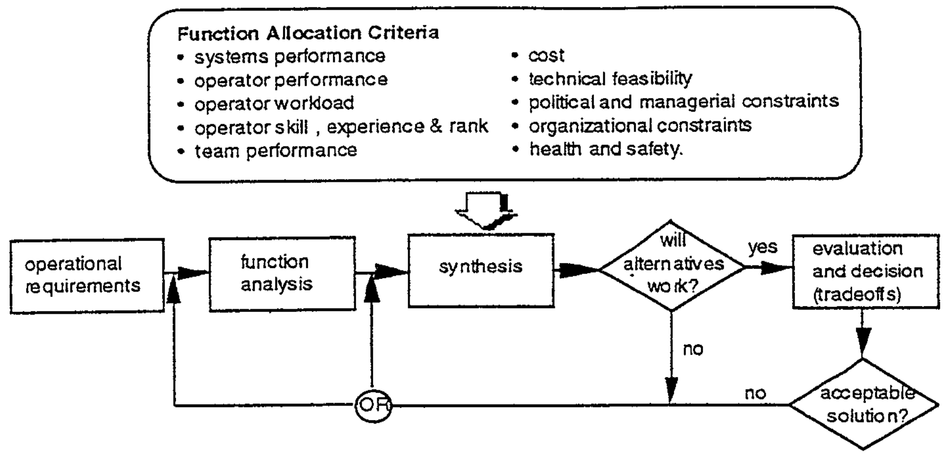

Figure three. Function allocation criteria used in practical applications

Several reports to the workshop showed how those factors could be addressed on a practical level. The analysis of skill requirements can be part of a multi-stage function allocation process (Goom, 1996). One case explored operator skill and ability through experimentation (Boer, 1996) and one (Knapp, 1996) showed how an existing taxonomy of skills and abilities (Fleishman and Quaintance, 1984) could be adapted and used to match task demands to the potential users of a system.

Teamwork, rank structure and the user's organisation were also emphasised by several reports. It was argued that human factors considerations should be broadened to consider issues such as teamwork and the integration of the user's organisation (Aymar, 1996). One case study reported an application where analysis of rank structure was sufficient to influence the allocation of functions (Beevis, 1996). The same study showed that crew, or team, performance functions such as consultation, crew performance monitoring, maintenance of alertness, training and career progression were not included in the system functions decomposed by the systems engineers from the description of the system missions. Some issues of operator rank that affected the allocation of functions were identified only through field trials using actual operators (Streets & Edwards, 1996).

6. Practical function allocation techniques

No novel techniques for function allocation were discussed at the workshop, although several applications of improvements to existing approaches were reported. The approaches to making the function allocation decision which were reported included:

- a simple dichotomous choice between human and machine (Boer, 1996) based on a functional description of the system (Berheide, et al., 1996);
- a two-stage allocation process: one using a conventional initial analysis followed by one focusing on human functions which would benefit from decision aids (Essens & Campbell, 1996); another involving a conventional analysis of relative capabilities followed by one based on economics (Bost & Oberman, 1996);

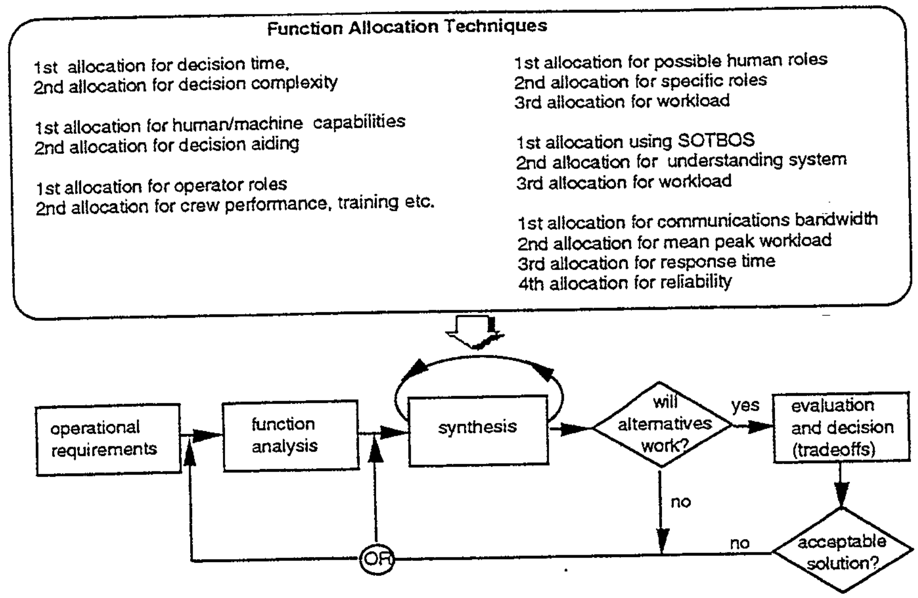

Figure four. Successive sequences of function allocation during design synthesis

- a three-stage process, first allocating to humans the tasks at which they are clearly best using SOTBOs, second, assessing what the human needs to understand the system, then third, assessing operator workload associated with the allocation decisions (Goom, 1996);
- a three-stage process based on that recommended by Rouse (1986, 1991), with an initial design phase where functions allocated to humans are converted to tasks and an operator interface, a second, design integration, phase which focuses on relationships between multiple tasks at similar points in time to improve performance and reduce workload, and a final design phase in which earlier decisions are reviewed and the possible application of dynamic function allocation is investigated (Nordø & Bråthen, 1996);
- iterative modification of function allocations, (McDaniel; Berheide, et al.; and Swartz & Wallace, 1996)
- reverse engineering of operator tasks (Malone, 1996) or retrospective analysis of tasks based on existing systems (Papin & Ruisseau; Knapp, 1996)
- adaptive (situation-dependent) allocation of any functions to human or machine (Berheide, et al.; Onken, 1996).

Thus in the majority of applications a successive application of function allocation criteria was used (authors' counts of 'stages' do not permit direct comparison between most approaches). They represent several inner development loops within the design synthesis activity, each one taking account of additional function allocation criteria (Figure 4). Such approaches are distinct from 'outer loop' iterations of function allocation decisions that include an evaluation and validation of a design option in order to examine the implications for the operators' tasks and the hardware specification (Singleton, 1974).

Dynamic Function Allocation.
The need to achieve a dynamic allocation of functions was supported by reports that 'static' allocations of function do not work well in some systems. This is because there are changes in the allocation of functions between team operators during missions lasting several days, and a single, 'static' allocation of functions may be inappropriate for such systems (Streets & Edwards, 1996).

As noted by Singleton (1974), an effective approach to dynamic allocation of functions can be achieved through supervisory control where operators can allocate responsibility for successive levels in a hierarchy of control loops to machine control (Sheridan, 1996). Currently, adaptive allocation of functions is being approached from two directions: the operator-driven approach considers the actual state of the operator which can be identified either by measuring or modelling of operator performance; the event-driven approach considers critical situation events which arise during a mission, e.g., by state changes of the tactical situation or the system. Berheide, et al. (1996) argued that the basis of every adaptive system is the event-driven approach which later can be supplemented by the operator-driven approach. Partnership means that the capabilities of the partners are similar, but not necessarily identical. Partnership demands effective dialogue, thus, for example, in the aircraft case, knowledge about the cockpit crew is crucial (Onken, 1996).

7. Evaluation of the function allocation decision

Many of the reports of applications made it clear that, with present approaches, it is important to test function allocation decisions as early as possible in the system development process. This may suggest predictive weakness in available function allocation techniques; more likely it reflects the many criteria which are involved in the decision. In this sense the approaches reflect the iteration used in some mathematical optimisation techniques, such as the Simplex method of linear programming, which progress from a basic feasible solution to an optimal solution through successive iterations.

Most reports focused on evaluating the implications of the allocation decision for system performance and operator workload rather than on using criteria related more directly to the allocation of function decision. This is because the function allocation decision can be evaluated only in the context of the consequences for the operator's tasks, workload, and resulting performance. This approach is the same as that recommended for systems engineering, in which a design solution is synthesised and evaluated and the design decisions modified until the evaluation criteria indicated that satisfactory performance will be achieved (Figure 2). In that respect, function allocation is part of the process of design synthesis, as noted earlier.

Evaluation criteria which had been used or were recommended included (see Figure 5): task performance (Boer; Knapp, 1996), operator workload (Boer; Goom; Malone; Swartz & Wallace, 1996), crew and system effectiveness (Beevis; Bost & Oberman; McDaniel, 1996), system operability, usability, maintainability, support-ability, survivability, and safety (Malone, 1996), operator responsibility (Streets & Edwards, 1996), compliance with specifications (Aymar, 1996), operator response to the system (Onken, 1996).

Methods which workshop participants had used or were suggested for evaluating the implications of function allocation decisions fell into the three categories of techniques used by system engineers for performance evaluation (Nordø & Bråthen, 1996):

- analytical modelling - analysis of the implications of the decision for various evaluation criteria (Beevis; Bost & Oberman; Goom, 1996); this could include a 'walk-through' of a design proposal, or virtual-reality prototyping (suggested by

Papin & Ruisseau, 1996) during which the implications for systems performance are analysed

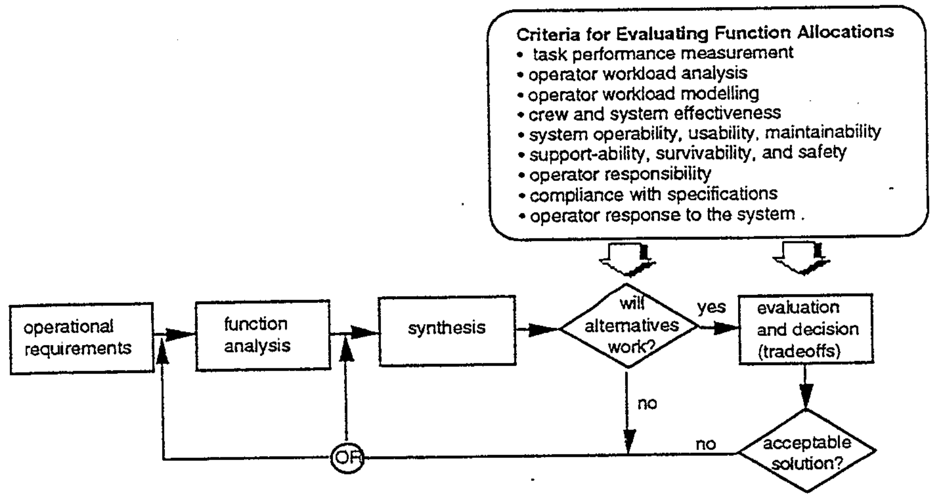

Figure five. Criteria used for evaluating function allocations

- simulation - fast-time computer simulations of operator tasks and workload (Knapp; Malone; Swartz & Wallace, 1996)
- measurement - using: rapid prototyping (Berheide, et al.; Nordø & Bråthen, 1996); human-in-the-loop simulation (Boer; McDaniel, 1996) or; field trials (Streets & Edwards, 1996).

Concern was expressed by some participants about the validity of some evaluation techniques, particularly fast-time computer simulations of operator workload. It was noted that, to some extent, humans are placed in systems because we do not know enough or cannot anticipate enough all the circumstances in which a system will operate. Therefore it is impossible to validate function allocation decisions completely even in the test phase. Techniques such as computer simulations were being subjected to validation for tasks which were known and described.

8. Summary of the NATO Workshop

The NATO workshop on Improving Function Allocation for Integrated Systems Design had four aims: to review the need for function allocation, the maturity of available techniques, the need for additional research and to make recommendations to human factors practitioners.

The Need For Function Allocation

The workshop concluded that function allocation is necessary and increasingly important. Function allocation is the process in which knowledge concerning human performance and other constraints is coupled to potential solutions. From the human factors perspective the problem of function allocation is to develop "proven" combinations between human performance characteristics and (generic) solutions. The Fitts' list and derivatives must be interpreted this way.

The Maturity Of Available Techniques
The overall approach to function allocation recommended in the human factors literature does not appear to have matured very much in three decades. What became clear at the workshop was that workable approaches are not the simple choice between humans and machines that is so frequently suggested in the literature. Because available allocation techniques are essentially qualitative, function allocation decisions can only be validated by predictions of operator workload or system performance in the future system.

Recommendations To Human Factors Practitioners.
The major recommendations to practitioners which were derived during the discussions of the NATO workshop addressed the nature of function allocation, the need to work within the constraints posed by the systems design team, and the range of techniques that can be used.

Recommendation 1: Function allocation is essentially a creative process associated with the design of a system within the overall development cycle of 'analysis' 'design' 'test and evaluation.' As such, function allocation does not lend itself to a mechanistic approach or to automation, although the process can be facilitated by computer-based tools and integrated design and development teams.

Recommendation 2. Human factors specialists must establish their procedure for implementing function allocation within the constraints posed by a particular project. Integrated design teams provide the working climate necessary for the early and effective interchange of data and concepts on the role of the human. Many allocation criteria must be taken into account. If human factors practitioners work within the systems engineering process, they are more likely to be aware of the various trade-off criteria and the constraints which apply to the system design solutions.

Recommendation 3: To assist the interchange of such data and concepts, practitioners should select approaches to function allocation that are understandable by systems engineers and designers. Because computer scientists, systems engineers and human factors specialists use the term 'function allocation' for different activities and because the terms 'function' and 'task' have different meanings depending on the user, practitioners should use clearly understood, common definitions of such terms within their specific projects.

Recommendation 4: No one technique for function allocation can be recommended to human factors practitioners. Several viable approaches for function allocation are available and can contribute to the development of advanced systems provided that they are applied at the correct point in the systems engineering process. Quality assurance requires that the criteria used for assessment, or evaluation, match the criteria used in the function allocation process. As noted earlier, however, the criteria used for function allocation may not support quantitative evaluations. The development of the system design and the use of experiments or simulations permit the use of interval or ratio-scale criteria for evaluating the function allocation decision (compare the criteria in Figure 5 with those in Figure 3).

9. Discussion

The workshop underlined the need for Function Allocation and concluded that function allocation is increasingly recognised as a way to incorporate human factors in the design process. The most important reason for giving attention to function allocation is the reduction

of the human cost and risk factors. Systems designers, developers and procurement people welcome any means for reducing the risk of developing a sub-optimal system, as long as it fits into their model of development and it clarifies issues instead of complicating them. Unfortunately, few texts on system design methodologies include human factors activities (except for occasional references to hardware ergonomics). Despite that, it is our experience, confirmed by the workshop papers, that there is much interest in the assessment of the role of humans in systems and the impact technology has upon this role.

There seems to be a dissociation between the methods frequently recommended in the human factors literature and the practical approaches to function allocation taken by the workshop participants. Presentations showed practical approaches that are not a simple choice between humans and machines but include training and skills or abilities as criteria in the function allocation process. The emphasis that several workshop presentations placed on including criteria related to organisational issues, and, in the case of military systems, rank structure, is interesting in the light of the claim that current allocation techniques ignore such issues (Robson, Hornby, Clegg, MacLaren, Richardson, & O'Brien,1991).

Function allocation is part of an 'analysis-design-evaluation' development cycle. The workshop presentations showed that practitioners put effort into analysis using a more or less comprehensive sets of criteria, and/ or into testing or evaluating tentative system options. There was little mention of the creative process of integrating these issues in the development of design options. The move from function allocation issues to a design solution is still a 'creative leap' rather than a defined step. As such it does not compare to the kind of problem solving in which analysis eventually leads to 'discovering' the one right solution. This leads to the conclusion that developments in function allocation should focus on better analysis techniques using more human factors parameters, better test methods and fast iterations in order to get feedback on the direction of the system development. Still there is room to support the creative process. A compilation of a 'Reference' file which contains known (partial) function allocation solutions and effect evaluations from particular domains is one approach to help to predict the consequences of particular allocation choices (Essens, et al, 1994).

Evaluation is often seen as an activity that comes at the end of the design activities, as a test that proves the functionality of the system. To us, evaluation is an activity that runs concurrently with the analysis; it is essentially a more or less formalised step away from analysis and design in order to look at the (intermediate) results of the ongoing work from an outside perspective. The aim is, foremost, to find out whether the results of work have brought the goals of the development any closer; in a sense this is a quality check. This requires a close coupling between the goals and criteria specified in the analysis activity and the evaluation criteria.

Iterative development is, in this context, one or more recursive passes through analysis, design and evaluation activities. Reference to iteration was found in the workshop reports as steps or stages in the allocation process, in most cases as inner loops of the design synthesis process.

Iterative development is a requirement that comes from the fact that most problems are so complicated that they cannot be solved in one pass. One iteration model started with 'obvious' and common sense allocations, followed by two passes with criteria related to 'understanding' the system and workload criteria. In line with a general 'breadth-first' problem solving and planning approach, the iterations should progress from general to detailed issues, starting with those criteria that have a large impact on the success of the development and the performance required of the system. A 'practical' approach should avoid having to revise earlier design decisions because of a late discovery of a critical criterion or constraint. There does not seem

to be a common understanding on which criteria or which aspects are pertinent to the early iterations, judging by the different 'stages' mentioned in the workshop papers.

A difficult aspect of iterative development is to find a balance between profound analysis and quick and dirty design-test-modify cycles. Comprehensive analysis will maximise the chance of identifying crucial constraints that should be covered early on in the development of the system. because when the system becomes more concrete only small adjustments will be possible. This approach however will take time without tangible results, moreover if it is a new system not all constraints will be found or recognised as constraint by mere analysis. The quick and dirty approach will have a risk of going in a direction that is will prove to be wrong, which could have been avoided if one had put some more effort in thinking before doing. Moreover, The more human factors practitioners understand about the problem domain the more they are better able to predict future system performance which will greatly increase the effectivity of analysis. It was noted at the workshop that there is lack of information about the effects of particular allocations at an early conceptual level of development. One way that this question might be answered could be by the systematic compilation of information about function allocation issues, a taxonomy, relating to the problem domain, the criteria for function allocation, and the techniques appropriate for function allocation in that domain.

The way ahead.

Several important research issues related to function allocation can be identified. Starting with the analysis of the system a crucial issue is the development of the role of the human in the system. This can only partly be derived from logical analysis, rather this should be based on principles. Therefore, research should be focused on the implications of the role of humans in future systems having a high degree of autonomy and the implications of treating the human being as a system component compared to treating the system as a means of supporting human responsibilities. Also for analysis, a comprehensive description of the human-factors criteria and their inter-relationships should be developed, including a trade-off matrix that helps weighting the relative contributions of the criteria.

For the synthesis process, a reference base and a taxonomy should be developed from allocation applications in different domains. If there is a common set of well-defined criteria it will be easier to compare between applications. For the evaluation process, lean and quick computer-based test methods should be developed and validated that link system goals and measurement of the criteria. For the process as a whole, an iteration model should be developed representing inner and outer development loops, that specifies how to determine what criteria (and which detail) should be addressed on the different levels of system specification.

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